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FINAL REPORT

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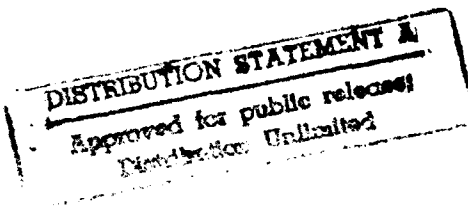
ACTIVE CONTROL OF PRESSURE OSCILLATIONS IN
LIQUID-FUELED PROPULSION SYSTEMS

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Research Objectives

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This program has been devoted to analytical work motivated and guided by experimental results obtained largely by other organizations. The three primary research objectives are

- 1) representation of linear and nonlinear combustion instabilities, encompassing all contributions to energy gains and losses, including noise sources, in a form suitable for application of active control;
- 2) modeling unsteady combustion processes and their coupling to unsteady flow fields;
- 3) application of control theory, analysis, and design to combustion chambers, with particular attention to robustness in the presence of uncertain variations of parameters. Although not addressed in the past two years, eventually application of methods of nonlinear control will be investigated.

The personnel involved in this work have also participated to some extent in planning laboratory tests and /or interpreting data taken at Caltech and by other groups, including the Naval Weapons Center and the General Electric Company. Our eventual goal is to engage in the development of methods and strategies for treating combustion instabilities in laboratory tests and operational systems.

Personnel, Collaborations and Related Works

In addition to the principal investigator, a post-doctoral Research Fellow (C. Jahnke) and a graduate student (W. Lin) have been supported by funds provided in this program; the graduate student received his stipend as a teaching assistant during the academic year September 1990 to June 1991. Two Research Associates have also participated, one partially supported by this program (J. Sterling) and one (N. Dethienne, a visitor for 18 months) supported by the French propulsion company, S.E.P.

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We have continuing collaborations with the Naval Weapons Center (Dr. Schadow et al); the Caltech controls group (Prof. Doyle and students); Carnegie Mellon (Prof. Paparizos); Penn State University (Prof. Yang and students); and the General Electric Company (Dr. Mehta, who plans to provide us data taken in laboratory tests).

Related experimental work, funded by AFOSR, is in progress at Caltech under the direction of Prof. E. E. Zukoski. We have appealed to and intend to make further use of data taken in that program.

Summary of The Work

Consistent with our research objectives, most of our work has been concerned with extending application of our approximate analytical framework to provide more complete understanding of the unsteady motions observed in combustion chambers. Spectra of pressure oscillations typically show peaks, with broadband content over a wide range of frequencies. Although the peaks are often identified with classical acoustics, it is common also to find discrete frequencies not so classified, and likely the consequence of nonlinear behavior. The broadband portion may be due either to stochastic sources (noise produced by flow separation, turbulence, turbulent combustion, . . .) or possibly, yet unproven, due to deterministic chaotic behavior. Our analytical work, combined with analysis of experimental data, has been directed to interpreting the details of spectra and to providing the understanding of the general problem necessary for application of control theory.

The basis for our work is an approximate analysis based on perturbation analysis of the general conservation equations and application of a form of Galerkin's method to produce, after spatial averaging, a system of ordinary differential equations in time. That set of second order equations provides a view of unsteady motions in a combustion chamber as a system of coupled nonlinear oscillators, one oscillator associated with each mode in the Galerkin expansion. This formulation allows us to use contemporary methods for studying nonlinear dynamical systems. Most of our previous work has been based on the time-averaged equations, greatly simplifying the calculations and providing a convenient framework for routine analysis of operational combustion chambers. Part of the work accomplished during the present program has been concerned with determining the limits of accurate results obtained with time-averaging.

The work divides into three tasks, one of which (the last listed here) has been supported only partly by this program.

1) Application of bifurcation theory and continuation methods to nonlinear acoustics

The purpose of this work, based on the nonlinear equations derived with the approximate method, is to determine the existence and stability of limit cycles, and the occurrence of bifurcations. With the numerical continuation method we have applied, we are able to investigate nonlinear behavior to large values of the linear parameters (growth constant and frequency shift). Moreover, the method will be applicable to higher order nonlinear gasdynamics (only second order has been treated) as well as to arbitrary geometries and nonlinear combustion.

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An important consequence of this method is that it permits assessment of the limits of time-averaging. The limits cannot be set in a literal sense, but are inferred from the numerical results. A survey of results obtained over the space of linear parameters may provide a guide to the limits.

2) Application of the approximate method to thermally-driven oscillations in a Rijke tube

This analysis has been carried out partly in support of laboratory tests at Caltech and partly as the simplest example of our approximate analysis. The energy source in this case is a heated wire coil. Results for linear stability show good quantitative agreement with previous and current experimental results for the conditions under which oscillations are excited. The nonlinear analysis has been formulated but results of comparison with data have not yet been completed.

3) Distinguishing noise and deterministic chaos

This work was begun independently of the current program but during the past year the investigator, Dr. J. Sterling, has become an active participant. He has been applying a method of analyzing time records to determine the dimensions of attractors, to data he took several years ago with a laboratory dump combustor at Caltech. His results show (apparently) the existence of a two-dimensional attractor. That behavior may be due either to nonlinear combustion processes or to nonlinear gas dynamics, or both. We have no definite answer at this time. Previous results with second order nonlinear gasdynamics and linear combustion predict the existence of periodic limit cycles (one-dimensional attractors) but recent results obtained with application of bifurcation theory (task 1 above) suggest that under some conditions higher dimension attractors may exist due to the nonlinear acoustics only. However, nonlinear combustion processes may equally be a cause, as Dr. Sterling has found in early results. Presently the relative importance of nonlinear acoustics and nonlinear combustion cannot be thoroughly assessed.

Publications

The following publications have been based partially on this program. The third, to be presented in June, 1991, is to a large extent a summary of the work described here and is appended as Attachment A. Further results have been obtained since the preparation of that paper and are in the process of being documented. Also included in this list are internal memos which have not been distributed outside our group, but copies are available upon request. The substance of those memos will eventually be submitted for publication in refereed journals.

Culick, F. E. C. (1989) "Combustion Instabilities in Propulsion Systems" ASME Winter Meeting, San Francisco, CA (December 1989)

Culick, F. E. C. (1990) "Some Recent Results for Nonlinear Acoustics in Combustion Chambers " AIAA 13th Aeroacoustics Conference, AIAA Paper 90-3927 (October 1990)

Culick, F. E. C., Lin, W. H., Jahnke, C. C., and Sterling, J. D. (1991) "Modeling for Active Control of Pressure Oscillations in Combustion Chambers" American Controls Conference, Boston, MA (June 1991)

- Jahnke, C. C. (1990a) "Analysis of the Second Order Nonlinear Acoustics Equations With Two Modes," Caltech Guggenheim Jet Propulsion Center Documents on Active Control of Combustion Instabilities, Document No. CI90-1
- Jahnke, C. C. (1990b) "Introduction of Results Obtained by Continuation of Periodic Orbits," Caltech Guggenheim Jet Propulsion Center Documents on Active Control of Combustion Instabilities, Document No. CI90-3
- Jahnke, C. C. (1991a) "Limit Cycle Behavior of Second Order, 2,4,6 Mode Approximations to Nonlinear Acoustics in Combustion Chambers, I. First Mode Instability," Caltech Guggenheim Jet Propulsion Center Documents on Active Control of Combustion Instabilities, Document No. CI91-1
- Jahnke, C. C. (1991b) "Limit Cycle Behavior of Second Order, 2,4,6 Mode Approximations to Nonlinear Acoustics in Combustion Chambers, II. Second Mode Instability," Caltech Guggenheim Jet Propulsion Center Documents on Active Control of Combustion Instabilities, Document No. CI91-2
- Sterling, J. D. (1990) "Characterization of the Nonlinear Dynamics of Experimental Signals: Distinguishing Between Noise and Chaos," Caltech Guggenheim Jet Propulsion Center Documents on Active Control of Combustion Instabilities, Document No. CI90-2